157. Gardner RM, Chapman RH. Trouble-shooting pressure monitoring systems: When do the numbers lie? Chapter 7 pp 145-163. In Cardiopulmonary Critical Care Management Edited by Robert J. Fallat & John M. Luce. Churchill Livingstone New York 1987.

7

Trouble-Shooting Pressure Monitoring Systems: When do the Numbers Lie?

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Radene H. Chapman

Intensive care monitoring usually brings to mind electrocardiographic (ECG) and blood pressure monitoring. The use of complex monitoring equipment is only 25 years old and the routine use of monitors in clinical practice is still not very mature. A recent NIH consensus conference on critical care medicine revealed that monitoring technology has far outstripped our ability to measure the effectiveness of these tools.[1] There is also concern about a more basic question "Do the bedside monitors give us the right numbers?" The bedside physiologic monitor is the cornerstone of the modern intensive care unit (ICU). Out of the estimated 75,000 adult pediatric and neonatal intensive care beds operating in the United States, almost all are equipped with some type of physiologic monitor. The simplest of these monitors might only display an EKG signal and a heart rate, and have a simple high and a low heart rate alarm limit. More sophisticated monitors might also analyze the EKG, monitor intravascular pressures and respiratory status as well as mixed venous and arterial oxygen saturations. Bedside monitors have become more and more sophisticated, especially in the past 5 years. The introduction of digital computers into bedside monitors has revolutionized the acquisition, display, and processing of physiological data. Today, the newest commercially available bedside monitors contain multiple microcomputers and have more computer power than earlier computer systems that filled entire rooms.[2]

With the increase in computer technology and especially the presentation of data in a digital format, one may get the false assurance that what is displayed is "true." However, the admonition "user beware" is certainly applicable to physiologic monitoring equipment. Although bedside monitors can acquire and process physiologic data with remarkable speed and sophistication, monitors are still not perfect. Monitoring technology has not advanced to the point where common sense can be eliminated. In fact, we are sometimes disarmed by the sophistication of the monitoring equipment, believing that all systems are perfectly adequate.

Recent studies have shown that we should be ever vigilant of results obtained from monitoring systems.[3] Monitors do not always report the "truth." One study of blood pressure monitors, for example, showed that errors of 5 to 10 mmHg were frequent, and errors as large as 30 to 40 mmHg were not uncommon.[4] Recent

sophistication in pulmonary artery pressure monitoring algorithms has given one the impression that these monitors eliminate effects of respiratory variation, artifact, and perform "magic" to derive "truth."[5] In fact, the pulmonary artery pressure signal is one a trained human observer has difficulty analyzing.

OVERVIEW—OBTAINING ACCURATE PRESSURE DATA

Systemic and pulmonary arterial pressure are physiologic variables that reflect the consequences of cardiac output, peripheral or pulmonary vascular resistance and other hemodynamic factors. Figure 7-1 is a block diagram of a typical pressure-monitoring system. The patient is the source of the pressures that need to be measured. To measure these pressures a catheter must be inserted into a blood vessel or heart chamber. The catheter is usually attached to pressure tubing, a continuous flush device, and a pressure transducer. The combination of catheter-tubing-flush-transducer is known as the plumbing systems. The transducer is connected to an amplifier system that also provides transducer excitation voltage. Typically the amplified pressure signal is passed through a low-pass filter to "smooth" the pressure waveform before it is processed. Pressure monitors currently in widespread clinical use process the waveforms to derive clinically useful variables such as systolic, diastolic and mean blood pressure, and heart rate. These variables are displayed on the bedside monitor, stored for graphic presentation of "trends," evaluated to determine if preset alarm conditions have been exceeded, and transmitted to remote displays and computers.

Each step in the process of acquiring, displaying, and presenting the derived data can result in errors. These errors can result from an inadequate plumbing systems, improper transducer zeroing and calibration, and from the processing algorithms within the bedside monitor. For example, a catheter-tubing-transducer

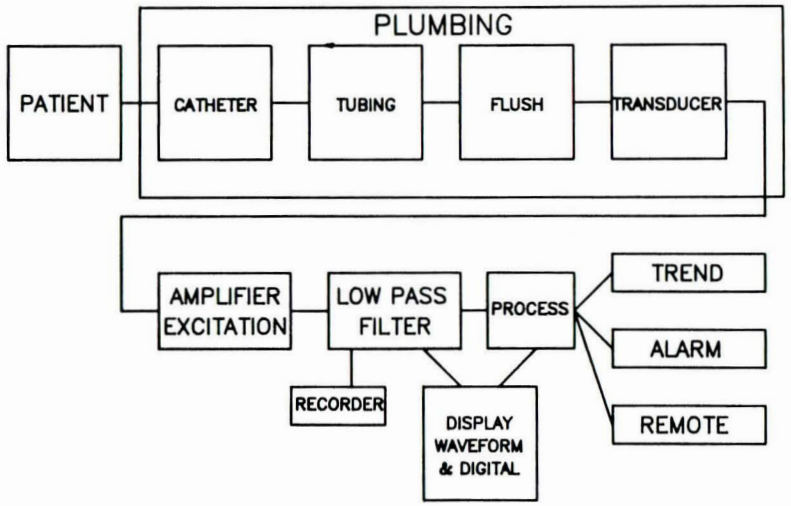

Fig. 7-1. Block diagram of a pressure-monitoring system showing the components that affect the accuracy of the results. The upper part shows the patient and attached plumbing system while the lower part shows components of the pressure-monitoring system usually contained in the bedside monitor.

system that contains air bubbles will typically have overshoot and result in a false elevation of systolic pressure. The bedside monitor may have low-pass filters to help eliminate artifact in the pressure waveform, but this same low-pass filtering may prevent you from validating the dynamic responsiveness of the pressure monitoring system. Algorithms for deriving and updating the blood pressure on the monitor vary widely depending on manufacturer and give different results when provided with the same patient waveform data.[4] Clearly all of these factors must be resolved before accurate blood pressures can be obtained.

The most important steps in getting accurate data from instruments are to understand the measurement principles, have simple set-up procedures for establishing the measurement, and establish a standardized methodology to derive and report parameters. There is still much controversy about the accuracy of direct and indirect pressures. From my years of experience with blood pressure monitoring, it is clear that large errors can occur with both the direct and indirect measurement of blood pressure. Because invasive intravascular monitoring procedures involve higher cost, risk of infection, and other complications, one must always be concerned about the necessity and benefits of invasive monitoring. However, carefully established invasive monitoring techniques can minimize the risk to the patient and maximize the accuracy of the data being measured. For the foreseeable future, a large number of critically ill patients will require direct pressure monitoring. This chapter outlines problems associated with direct blood pressure monitoring and gives recommendations for optimizing the efficacy and accuracy of monitoring systems.

PULMONARY ARTERY PRESSURE MONITORING

Since its introduction, the balloon-tipped flow-directed pulmonary artery catheter (Swan-Ganz) has been widely used in intensive care units.[6–11] The ease with which it is usually inserted may lead one to conclude that pulmonary artery and wedge pressure (Pw) are easily and reliably measured. However, this is not totally consistent with data reported by the originators of the technique.[6,12]

The four criteria applied to assess the validity of pulmonary artery wedge (Pw) pressures[10] are:

1. Mean Pw must be less than the mean pulmonary artery pressure.
2. The phasic Pw recording must be consistent with an atrial pressure waveform.
3. Free flow should be present when the catheter is in the wedge position so that the tip is in free communication with fluid column to the left atrium.
4. Highly oxygenated blood must be aspirated from the wedge position.

The frequency with which errors occur in wedge pressure measurements and how they can be reduced by applying the above criteria have been delineated.[9–11] By identifying the technical problems with the fast-flush technique (detailed below), the rate of error can be reduced dramatically.[9–11] Figure 7-2 outlines the frequency of wedge pressure measurement errors.[13]

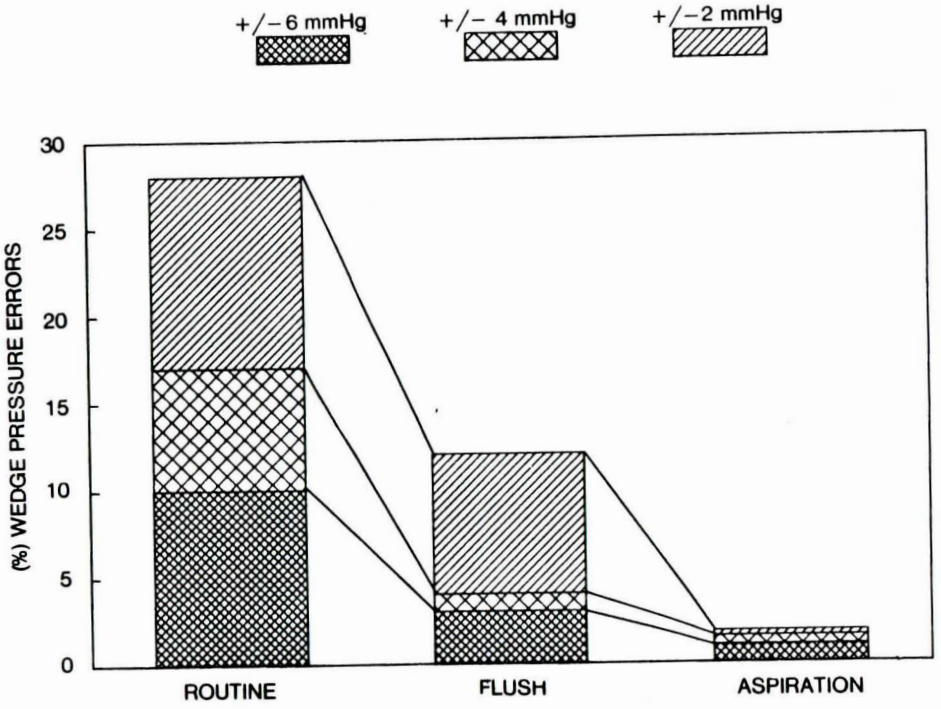

Fig. 7-2. Pulmonary artery wedge pressure errors and how they can be improved by application of waveform analysis and dynamic response testing. In the usual clinical setting, 28 percent of the wedge pressure measurements will be in error by ± 2 mmHg, 17 percent with errors of ± 4 mmHg, and 10 percent with errors of ± 6 mmHg. By identifying and correcting technical problems using waveform analysis and dynamic response (fast flush) testing, the error rate can be dramatically reduced, see second bar. For example, the rate of errors of ± 4 mmHg (considered to be clinically important errors) can be reduced from 17 to 4 percent. Further verification of wedge pressure measurements by aspiration of pulmonary capillary blood leads to a small further reduction in error (see third bar). The additive confirmation given by aspiration of wedge blood is not warranted with each measurement of wedge pressure in the clinical setting. (Cengiz M, Crapo RO, Gardner RM: The effect of ventilation on the accuracy of pulmonary artery and wedge pressure measurements. Crit Care Med 11:502 ©1983 The Williams & Wilkins Co., Baltimore.)

Pulmonary artery pressures can be measured accurately if the following steps are taken[9–11]:

1. Zero the monitor accurately.

2. Make strip chart recordings of all pulmonary artery pressures for a time period covering at least three respiratory cycles. Do not use digital displays.[4,13]

3. Perform and record dynamic response testing (fast-flush) for each position: wedge and Pa. If the response is not adequate, resolve the adequacy of the plumbing system before proceeding.

4. Obtain phasic (i.e., systolic and diastolic) as well as the mean pressures from the oscilloscope or strip chart recording at end expiration, when the transmural pressure is nearest zero. A display of respiratory cycle or airway pressures is useful to determine the end-expiratory period.

Table 7-1. Troubleshooting Guide for All Catheters

Problem	Cause	Prevention/Intervention
Blood backup in: catheter transducer flush device	Disconnection or leak in pressure system Low pressure (<300 mmHg) in pressure bag	Return stopcock to proper position Check connections frequently for tightness leaks Keep pressure bag inflated and flush solution replenished
Air bubbles in: catheter transducer flush device	Inadequate set-up of pressurized flush system Improper position of stopcocks Leaks or cracks in catheter or flush system	Careful set-up of continuous flush system (CFS) to avoid microbubbles Remove bubbles through stopcock if possible by placing the opening in a superior position and "tapping" the flush device so that air bubbles escape out the open stopcock port If there is a stopcock on the transducer dome, simply open the one-way stopcock on the side port and flush fluid and bubbles out of the system Transducers without side ports may require sterile disassembly to remove air bubbles
Inadequate or "damped" visual waveform	Air bubbles Leaks Catheter against vessel wall Blood in catheter Clot at tip of catheter Low pressure in bag No fluid in bag Kink in catheter	Remove air bubbles Check connections and CFS Flush catheter with flush device Irrigate catheter with syringe and normal saline Heparinized solution 2,000 units 500 ml solution helps keep clots from forming on catheter tip Check patient position (i.e., sitting with femoral catheter)
"Bad" fast flush Inadequate oscillations	"Damped" waveform (see above)	See above
Pressure stays >200 mmHg when fast flush released	Broken flush device	Replace flush device
"Pegging" on bottom of oscilloscope	Clot on catheter tip or tip against vessel wall (occlusion at tip)	Withdraw catheter 1–2 cm Irrigate catheter
Pressure <200 mmHg when fast flushing Cannot aspirate blood	Not enough pressure or fluid in flush bag Catheter against vessel wall Clot in catheter or at tip	Check for adequate pressure and solution in flush bag Aspirate clot if possible DO NOT force flush catheter If catheter irrigates easily, flush with syringe Withdraw catheter 1–2 cm Maintain continuous flush with heparinized solution
Cannot irrigate catheter	Catheter clotted or kinked Stopcock turned incorrectly	Look at catheter for kinks Check catheter for kinks Check position of stopcocks If catheter clotted, replace DO NOT force flush clotted catheter, aspirate clot if possible.
Tracing off top scale of scope	Stopcock mispositioned Catheter clotted Wrong scale on monitor Improper zero of monitor	Check stopcock position (See above) Change scale on monitor Check monitor zero

(*continued*)

Table 7-1. Troubleshooting Guide for All Catheters (***Continued***)

Problem	Cause	Prevention/Intervention
Cannot zero	Wrong monitor channel	Select proper monitor channel
	Bad pressure transducer	Replace transducer
	Bad monitor	Replace monitor
	Improper stopcock position	Check position of stopcocks
Kinked catheter	Acute angulation of catheter	Carefully secure catheter with loop—remove kinks
		Check patient position related to positioning of catheter
Broken catheter	Misuse of catheter	Prevent blood loss
	Defective catheter	Prevent air embolism
	Stress on catheter hub	Replace catheter
No waveform on monitor or strip recorder	Transducer not connected to catheter	Check monitor and stopcock position
	Monitor off, bad zero	Turn on and check monitor
	Catheter clotted	Aspirate clot from catheter
	Faulty transducer	Check and replace transducer
Wrong waveform on monitor or strip recorder	Wrong channel selected	Select correct channel
	Monitor malfunction	Check stopcock position
	Improper catheter position	Check for forward migration of pulmonary artery catheter
Broken flush device	Defective flush	Replace continuous flush
	Worn out	Clear catheter of blood
	Misuse of flush	Use properly
Damp dressings around connects or catheter insertion site	Loose connections	Check plumbing connections
	Cracked connections	Check catheter hub and catheter
	Worn connections	Check insertion site
	Infiltration of fluid from vessel or site	
Questionable low or high pressure reading	Improper zero	Rezero and check transducer position (hydrostatic)
	Change in transducer position	Check transducer calibration

Flush device: continuous flush device such as the Intraflo.
Bag: pressurized solution bag that provides flush solution for continuous flush device.
CSF: continuous flush system including the flush device and bag.
Damped: a smoothed out waveform with no sharp features.
Line: catheter and attached plumbing system for monitoring pressure.

5. Measure the pressures accurately and record them to document the patient's status and for future clinical decision-making.

Table 7-1 lists the problems that might be encountered when monitoring any direct blood pressure. Table 7-2 lists problems encountered specific to pulmonary artery pressure monitoring. Both Tables 7-1 and 7-2 list the problem, the cause of the problem, and how to prevent or intervene to correct it.

ARTERIAL PRESSURE MONITORING

It is desirable to have the arterial catheter tip advanced to a central location (i.e., the thoracic aorta or subclavian artery) since measurements at peripheral sites may not be accurate. Central arterial pressure provides the driving force for blood flow to the vital organs, heart, kidney, and brain.[15–17]

Tables 7-1 and 7-3 give troubleshooting information for use of arterial catheters.

Table 7-2. Troubleshooting Guide: Pulmonary Artery Catheter (Swan-Ganz)

Problem	Cause	Prevention/Intervention
No wedge when balloon inflated	Incorrect catheter position	Reposition catheter
	Inadequate balloon volume	Check proper inflation volume.
	Balloon ruptured	Assess competency of balloon.
		a. Resistance to inflation
		b. Able to withdraw all volume from balloon after inflate
		c. No blood or solution oozing from balloon port
		If balloon ruptured replace the catheter: DO NOT inflate further
Gradual pressure increase when balloon inflated: "overinflation"	Too much air in balloon	Withdraw some air from balloon until wedge pressure reappears
	Catheter tip too distal	Withdraw catheter 1–2 cm
	Balloon over tip of catheter	Observe pressure waveform during inflation to prevent
Wedge waveform present when balloon deflated: "permanent wedge"	Catheter too distal	Withdraw catheter 1–2 cm or until wave form appears
	Balloon left inflated	Have patient cough
		Deflate balloon
Partial wedge waveform when balloon deflated	Same as permanent wedge	See permanent wedge
Partial wedge waveform when balloon inflated	Catheter not in far enough	Advance catheter 1–2 cm
	Inadequate balloon volume	Reinflate to maximum volume
		Have patient cough
		Leave balloon inflated for a few minutes
Right ventricular waveform instead of PA waveform	Catheter has slipped back into the right ventricle	Watch for ventricular arrhythmias
		Inflate balloon and advance catheter
Too much artifact	Catheter whip	Interpolate values from a strip recorder
	Bad dynamic response	
	Rapid heart rate	

See footnote to Table 7-1 for definitions.

Table 7-3. Troubleshooting Guide: Arterial Catheters

Problem	Cause	Prevention/Intervention
Systolic pressure "overshoot"	Dynamic response artifact	Improve dynamic response of as noted in text. Install "damping" device if necessary
Decreased or absent distal pulse or Extremity cool and discolored	Thrombosis of artery	Check distal circulation frequently. Notify MD
		Remove catheter immediately
		Embolectomy if necessary.
Bleeding at insertion site	Coagulation problems	Apply pressure at insertion site.
	Blood leak around catheter	Apply pressure dressing or sandbag insertion site. Notify MD.

See footnote to Table 7-1 for definitions.

In general, zeroing errors are not as critical due to the higher pressures in the arterial system. In addition, the heart–lung interactions do not affect the peripheral artery pressures to the same degree that they do the pulmonary artery pressures. On the other hand, large pressure changes can occur, which may give artifactually high values due to overshoot. This is the most common condition that requires a damping device, which is seldom if ever needed in the pulmonary artery system. This condition should be suspected when manually measured systolic pressure is considerably below the catheter readings, a sharp, very steep, and short systolic curve is seen, and the high pressure does not coincide with the clinical evaluations.

GENERAL PRECAUTIONS FOR ALL CATHETER MONITORING SYSTEMS

1. Air should not be flushed through transducer setups in the pulmonary artery systems and *must not* be flushed through arterial or left atrial monitoring setups.

2. Left atrial catheters should not be used as a blood sampling site. They should *not* be disconnected for any reason and special care should be taken to avoid air embolism.

3. The use of sharp instruments should be avoided when removing dressings around the catheter site.

4. Intravenous drugs should *never* be administered through an arterial catheter unless the line was specifically placed for that reason (i.e., mesenteric artery line for Pitressin administration).

PLUMBING SYSTEM SET-UP AND EVALUATION

Zeroing the transducer is one of the most important steps in setting up a pressure-monitoring system. The patient's midaxillary line (right heart level) is usually used as a reference point. The zeroing process is used to compensate for offset caused by hydrostatic pressure differences, offset in the pressure transducer, amplifier, oscilloscope, recorder, and digital displays. Zeroing is accomplished by opening an appropriate stopcock to atmosphere and aligning the resulting fluid-air interface with the midaxillary reference point.[13,18,19] Figure 7-3 shows two transducer "zeroing" methods.

DISPOSABLE TRANSDUCERS

Standards have been developed for physiologic pressure transducers. For interchangeable transducers the AAMI/ANSI standard established the sensitivity at 5.0 μV/V/mmHg to within ± 2 percent of reading or 1 mmHg, whichever is greater.[20] Using standardized transducers will greatly simplify the interchangeability and use of direct blood pressure monitoring.

With the advent of disposable pressure transducers there has been increased interest in whether these devices are cost-effective. To answer this question a study was undertaken at LDS Hospital to assess the cost of reusable transducers. The base data was obtained from a 13 month review of transducer use. On average

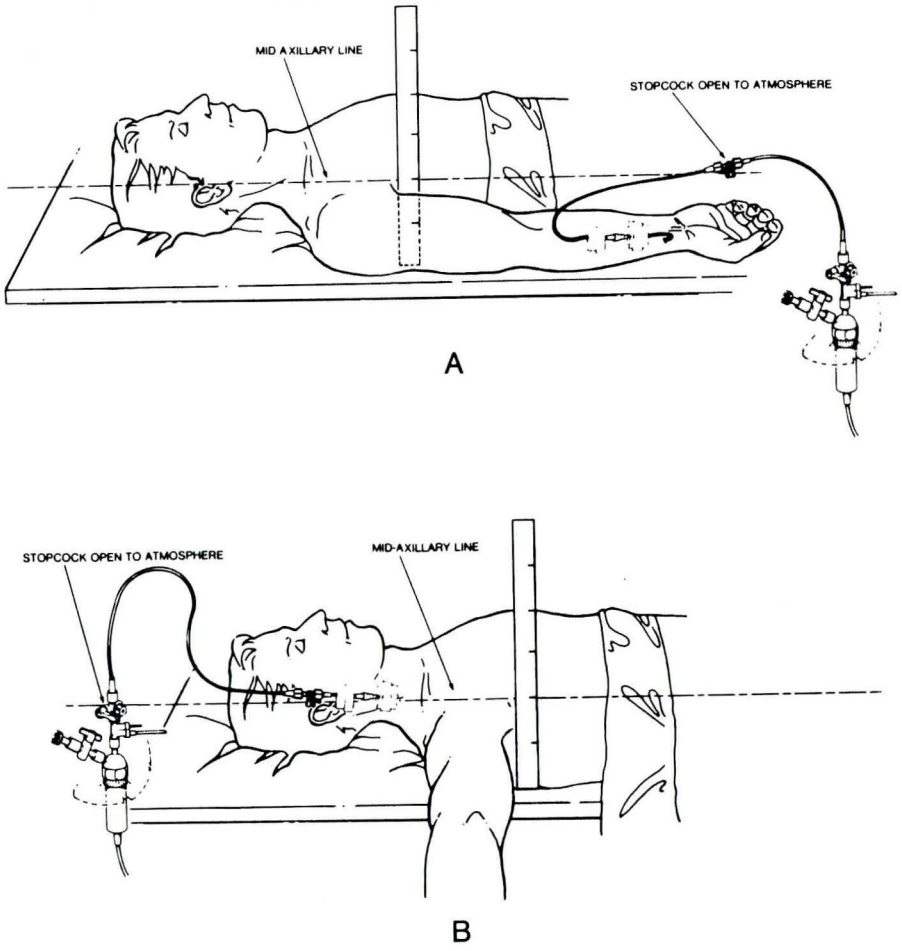

Fig. 7-3. Two methods of zeroing a pressure transducer. Note the place at which the water-air interface occurs must always be at the midaxillary line when zeroing. The stopcock is placed near the transducer at the midaxillary line (**A**). The stopcock near the catheter is placed at the midaxillary line (**B**). (Gardner RM, Hollingsworth KW: Optimizing the electrocardiogram and pressure monitoring. Crit Care Med 14:651, Copyright © 1986 The Williams and Wilkins Co., Baltimore).

there were 72 transducers available each month. During the 13 months transducers were used an average of 289 times per month (3,468 transducer uses per year). After reviewing records for a 3 year period, it was determined that reusable pressure transducers had an average life expectancy of 22 months (they are fragile and "disposable"). Each transducer was used an average of 4.01 times per month or about 88 times before it failed. The purchase price of the reusable transducer with appropriate calibrating connector box was $655. Therefore, cost for each use of the reusable transducer was $7.42. While in use these transducers required repair and recalibration at a cost of $3.46 for each use. To minimize the problems associated with use of disposable diaphragm domes, technicians cleaned, calibrated and resterilized each transducer between each use. Cost for this service was determined to be $7.54 per use. Thus the total cost per use was $7.42 + 3.46 +

7.54 = $18.42. Disposable transducers are now available that cost less than $15.00. In addition disposable transducers have the following advantages:

1. Cost effective.
2. State of the art transducer (which meets and maintain the ANSI/AAMI specifications): low drift, accurate calibration, and low zero offset.
3. Rugged: if the transducer works it will be accurate. Almost all transducer failures are of a catastrophic nature.
4. Small size.
5. All disposable transducers are from the same vendor and have the same characteristics; our reusable transducers came from a variety of manufacturers.
6. Future technology advancements will result in further price reductions for disposable transducers and they will become smaller and better.
7. Stocking of disposable for "peak" load time is no problem.
8. Assured sterility.
9. Smaller "volume displacement," which ensures better dynamic response characteristics.

Several excellent quality disposable pressure transducers are now available.[21] Figure 7-4 shows the wide variety of disposable transducers available in 1987. Disposable transducers also have better technical qualities and can better withstand the rigors of clinical use than the outdated reusable transducers.

FAST-FLUSH DYNAMIC RESPONSE CHECKING

Plumbing systems used in the ICU can be characterized as an underdamped second-order dynamic systems analogous, for example, to a bouncing tennis ball.[13,18,22] A second-order system can be expressed mathematically by a second-order differential equation. Dynamic response characteristics of catheter-tubing-transducer systems can be characterized by specifying their natural frequency (Fn) and damping coefficient (zeta).[18,21,22] Methods for measuring Fn and zeta are shown in Figure 7-5. For the clinical setting the acceptability of the response can be mapped into one of the five areas of the plot shown in Figure 7-6.[18,21,22] If the characteristics of the plumbing system fall in the adequate or optimal area of the graph, the pressure waveforms will be adequately reproduced. If they fall in the remaining three areas, there will be waveform distortion. Most catheter-tubing-transducer plumbing systems assembled under optimal conditions are underdamped, while a few fall into the unacceptable area. Methods for optimizing the plumbing system components have been outlined.[13,18,22,23] In the clinical setting there are dramatic differences between each patient set-up, therefore it is mandatory to test the adequacy of each pressure-monitoring system.[23] This can be done easily using the fast-flush technique.

The fast-flush is produced by opening the valve of the continuous flush device (for example, by pulling and quickly releasing the pigtail on an Intraflo). The rapid closure generates a square wave from which the natural frequency and damping

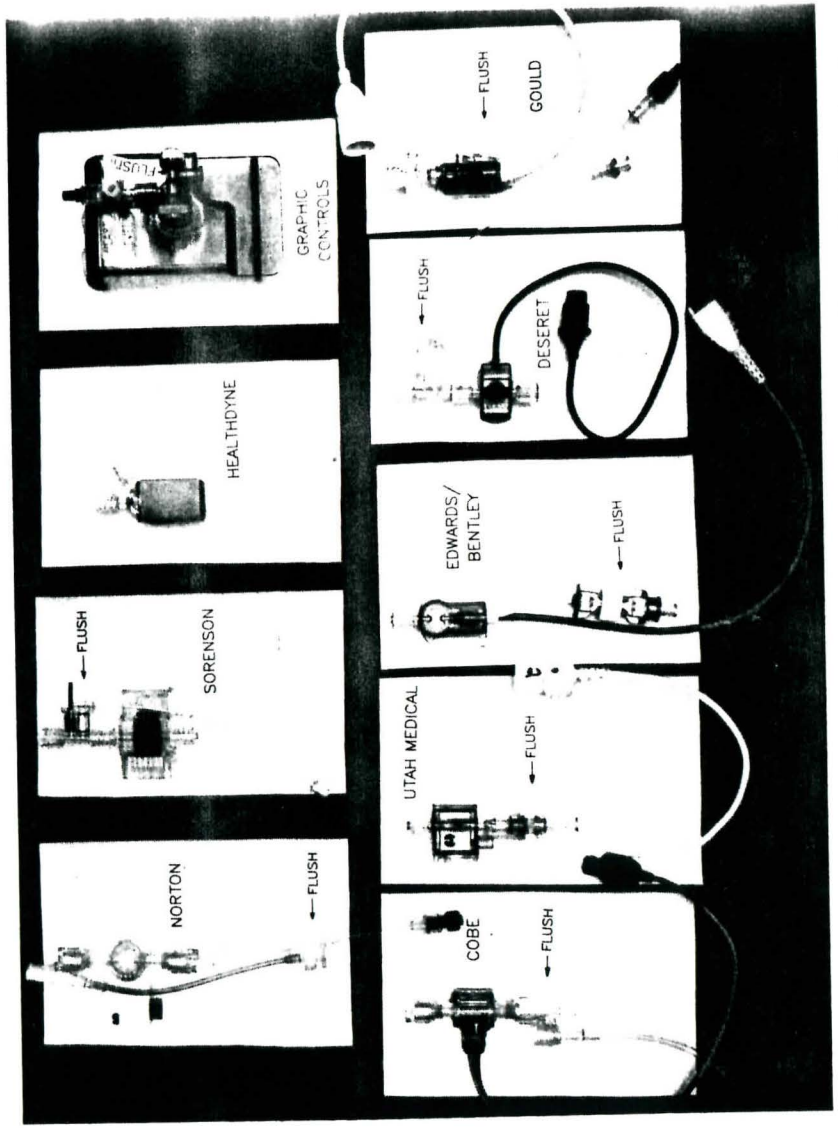

Fig. 7-4. Disposable pressure transducers showing their small size (all have standard Luer fittings). Note that there are a variety of configurations and cable connections. Most have integral flush devices. The four transducers on the top attach to their cables with internal connectors while the five transducers on the bottom connect with a "pigtail" cable. The Cobe (lower left) has a Linden fitting while all other have Luer lock fitting.

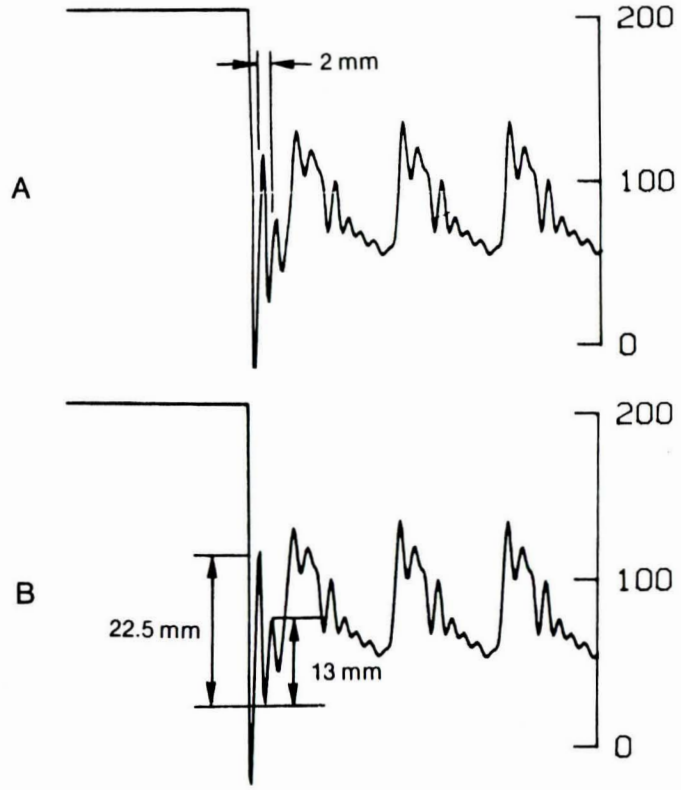

Fig. 7-5. How to measure dynamic response parameters. **(A)** The natural frequency can be determined by using a strip recording to measure the period of one full oscillation resulting from the fast flush. In the example shown, one full cycle is 2 mm. Since the paper speed is 25 mm/sec the natural frequency is $Fn = \frac{25 \text{ mm/sec}}{2 \text{ mm}} = 12.5/\text{sec} = 12.5 \text{ Hz}$. **(B)** Determination of damping coefficient requires the measurement of any two successive peak amplitudes. Then the ratio of these two amplitudes is taken. Amplitude ratio = 13/22.5 = 0.58. Using the amplitude ratio scale on the right of Fig. 7-6 we see that the damping coefficient is 0.17.

coefficient of the plumbing system can be measured. The dynamic response characteristics of a blood pressure monitoring catheter-tubing-transducer system can quickly and easily be determined in the clinical setting. The "fast-flush" method is ideal because the continuous flush device is already in place. This method also evaluates the entire system while it is in clinical use and it is quickly and easily performed—pulling on the flush valve and releasing it with a "SNAP" is all that is required (Fig. 7-5).

Since the fast-flush test has been executed two to three times, the dynamic response characteristics (natural frequency Fn and damping coefficient, zeta) can be quickly and easily determined.[13,18,22] The Fn can be estimated by measuring the period of each full oscillation on a strip chart recorder (see Fig. 7-5A), following a fast-flush, and calculating the frequency from the period. The damping coefficient is determined from the ratio of the amplitude of two successive oscillations as shown on Figure 7-5B. The list below outlines clinical recommendations for op-

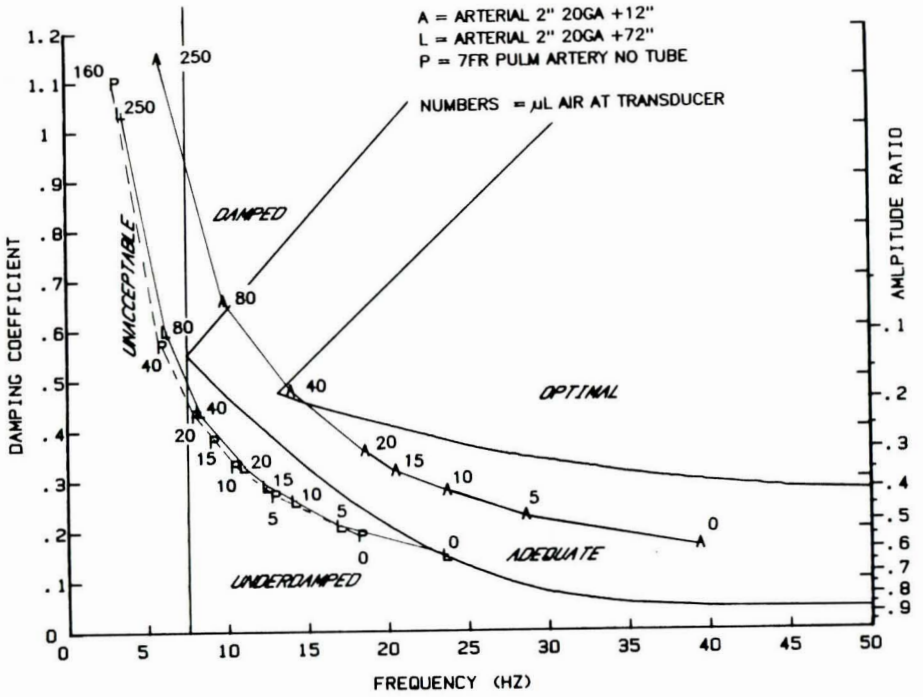

Fig. 7-6. Plot of natural frequency (Fn) versus the damping coefficient (zeta) for two arterial and one pulmonary artery pressure-monitoring systems showing the effect of inserting small bubbles at the transducer dome. The volumes (Vd) are shown near the marks on the curves and are indicated in microliters. The curves were generated as explained in the source. Results are presented for a short radial arterial catheters (Deseret 2 inches) with 12 inches of pressure tubing (Index A) and for a 72 inch tubing system (Index L). The results from a pulmonary artery catheter system without any extension tubing are indicated by P. Note that for both cases the operating point moves upward and to the left. The best operating conditions are achieved when there is *no* air in the system. This condition is always indicated by a high natural frequency. It is clear from the clinical evaluation that many of the pressure-monitoring systems had large amounts of air which resulted in and unacceptable dynamic performance. (Gibbs NC, Gardner RM: Dynamics of invasive pressure-monitoring systems: clinical and laboratory evaluation. Heart Lung, in press 1987, with permission.)

timizing dynamic response of pressure-monitoring system.[23] In general the optimal conditions can be obtained by removing air and minimizing tubing and connections. A separate damping device is rarely needed, usually only in central arterial lines.

Clinical recommendations for optimizing pressure-monitoring dynamic response are outlined here.[23]

1. Steps for optimizing dynamic response.
   A. Select monitoring "kits" that are simple with a minimum amount of pressure tubing and relatively noncompliant tubing, flush devices, and transducers.
   B. Remove all air bubbles during set-up especially near the transducer. Air bubbles in the side ports of three-way stopcocks are invisible and can be troublesome. Eliminate them by fluid filling all the ports of the

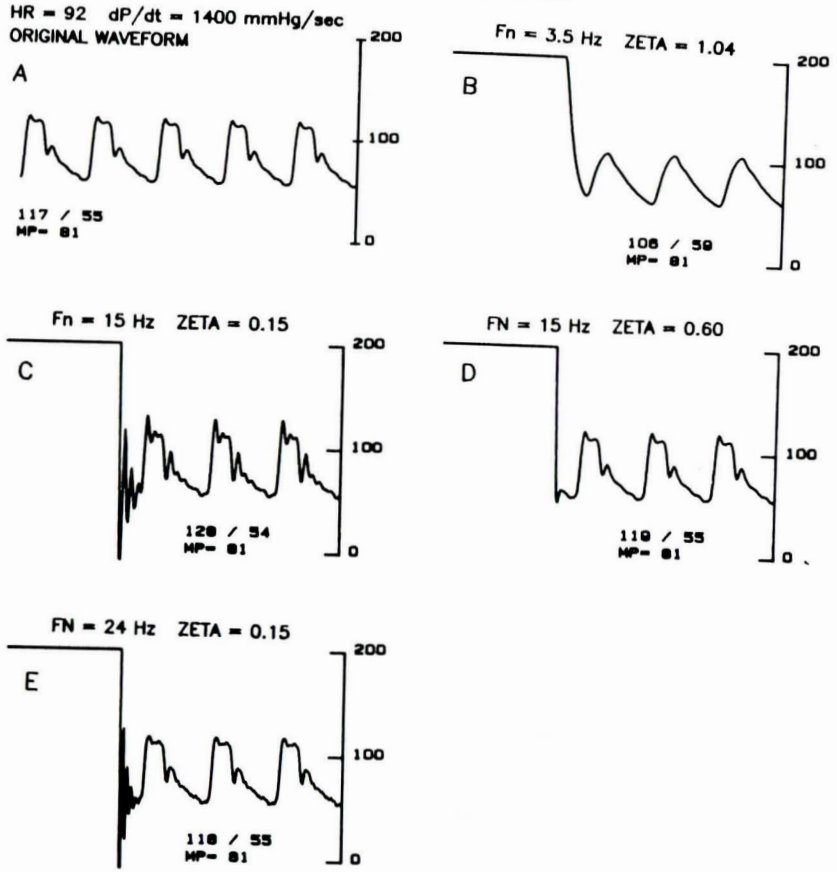

Fig. 7-7. Arterial pressure waveforms recorded with different pressure-monitoring systems. Patient heart rate is 92 with a maximum dP/dt of 1,400 mmHg/sec. **(A)** Actual waveform as it might be recorded by a catheter-tipped pressure transducer. The systolic pressure is 117 mmHg, diastolic 55 mmHg, and mean pressure is 81 mmHg. **(B)** The same patient's arterial waveform recorded with an "overdamped" system. Zeta 1.04 and Fn of 3.5 Hz. Note that the "fast-flush" signal (upper left) returns slowly to the patient waveform. Systolic pressure is underestimated (106 mmHg), diastolic is overestimated (59 mmHg), but mean pressure is unchanged at 81 mmHg. **(C)** shows an "underdamped" condition with low damping coefficient. Zeta 0.15 and Fn of 15 Hz. After the "fast flush" the pressure waveform oscillates rapidly. Systolic pressure is overestimated (128 mmHg), diastolic pressure is adequate (54 mmHg), and mean pressure is unchanged at 81 mmHg. **(D)** Same situation as **(C)**, but with a damping device inserted and adjusted.[22] The waveform is optimally damped pressure with a Zeta of 0.60 and Fn of 15 Hz. The undershoot after the "fast flush" is small and the original patient waveform is adequately reproduced. **(E)** "Underdamped" condition but with high natural frequency (24 Hz). Note that the waveform is only slightly distorted and that systolic (118 mmHg) and diastolic (55 mmHg) pressures are close to the true pressures. (Gibbs NC, Gardner RM: Dynamics of invasive pressure-monitoring systems: clinical and laboratory evaluation. Heart Lung, in press 1987, with permission.)

stopcock. If disposable diaphragm domes are used, be certain they are properly attached.

C. Minimize the potential for clot formation at the catheter tip by using a continuous flush system. Ascertain that there is not a clot in the catheter by "fast flushing" and, if necessary, aspirating blood from the catheter.

D. Eliminate kinks in the catheter or tubing.

E. Eliminate long lengths or compliant interconnecting tubing.

F. Use low-volume displacement transducers and flush devices. The new disposable transducers have lower volume displacements than most of the reusable transducers.

G. When all of the above steps have been taken and the system has a natural frequency greater than 7.5 Hz, use of a damping adjustment device is indicated.[18,22,23]

2. Optimize the natural Fn. As can be noted in Figure 7-5, if the Fn is maximized one obtains the best results. As the Fn increases, note that the damping coefficient remains about the same. Estimating the natural frequency by "eyeballing" a fast flush on an oscilloscope or by measuring it on a strip recorder is quick and easy and requires almost no computation.[22] For example if a strip recorder running at the usual speed of 25 mm/sec is used and the distance between peaks or valleys of one of the fast flush oscillations is 1 mm (1 box), the natural frequency is 25 Hz. If the distance is 2 mm (2 boxes), the natural frequency is 12.5 Hz (see Fig. 7-5A).

3. Recommended frequency of dynamic response validation.

A. At least once each shift

B. After each "opening" of the system such as for zeroing, blood drawing, or changing of tubing

C. Whenever the pressure waveform appears to be "damped" or otherwise distorted

PRESSURE-MONITORING ALGORITHMS, TREND PLOTS, AND ALARMS

Directly monitoring intravascular pressure provides timely, useful, and important data to those caring for critically ill patients. Extracting data from the arterial pressure waveform typically provides reliable systolic, diastolic, and mean pressures. However, during a recent review of three bedside monitors with pressure-monitoring capability,[4] it was found that none recognized and rejected the following three artifact conditions:

1. Zeroing the transducer: All the monitors tested "read" near zero on the digital display when the transducer was opened to air to zero the system.

2. Fast flushing the system to verify dynamic response: All the monitors tested displayed a fixed value for systolic, diastolic, and mean pressure when the arterial line was being flushed during routine care. None of the monitors identified this pressure as a "fast flush" or as artifact.

3. Drawing blood from the patient: When the stopcock near the transducer was turned off while drawing blood, each of the monitor's digital systolic/diastolic and mean pressure displays eventually stabilized at the pressure in the flush bag (usually about 300 mmHg) with no indication that a blood draw was occurring.

These findings show that the digital processing (and, as a consequence the displays) are not "smart" enough to distinguish between the patient's pulse pressure and zero, blood draw, or fast-flush signals that occur frequently in the ICU. These three conditions occur several times a day during normal patient care and result in false alarms and erroneous data being logged in the "trend" recording. At this stage of bedside monitor algorithm development, it appears that although the computerized measurement systems are technologically complex, they are not yet fully capable of recognizing abnormal arterial pressure waveforms. Many innovative algorithms have been developed for determining the pulmonary artery pressure.[5] The digital computer in this case should be capable of reading the pressures at end expiration and eliminating artifact and physiologic "noise."[7–11] At the moment none of the algorithms presently in use in clinical monitors performs these tasks well under all clinical conditions.

It appears that there is also a need for more sophisticated algorithms for the measurement of systemic arterial blood pressure, to eliminate erroneous data collection. Until algorithms in the bedside monitor are improved, clinicians should be aware of the differences between the measurement of arterial blood pressure obtained from a strip chart recording and those obtained from a digital display.[4] To validate systolic and diastolic blood pressure, arterial pressure waveforms should be displayed and reviewed on a calibrated oscilloscope or paper recorder before a digital reading is accepted.

Contemporary monitors do little to reject artifacts, and as a result, when artifacts occur, the bedside monitors present the erroneous data on their digital display, generate false alarms, transmit the erroneous data to the patient data management systems, and log the erroneous data into their trend memory.[24–27]

Because contemporary monitors have little ability to recognize zeroing, flushing, and blood drawing, efforts were made to enhance the algorithms of a Marquette 7000 series monitor to improve its artifact rejection capabilities.[24] The data used to compare the systems were obtained from FM analog data recordings taken from two different clinical ICU settings (Massachusetts General Hospital in Boston, MA, and LDS Hospital in Salt Lake City, UT).

We evaluated 32 different 5 minute epochs of patient data tapes obtained from 17 different patients. The ability of the algorithm to detect the three types of artifact was analyzed. In addition three physiologic conditions (asystole, cardiac failure, and physiologic changes in mean pressure) when a "true" alarm should have been generated were tested. Further, tests of several hours of data from the patient data tapes were evaluated to ascertain that the algorithm did not falsely alarm or miss significant physiologic events.

Results are shown in Figure 7-8. The solid lines show the results of the contemporary monitor while the boxes show the results obtained with the enhanced algorithm. The results shown are typical. There are two blood withdrawals followed by three groups of flushes and then a rezeroing of the transducer. It can be clearly seen that the enhanced algorithm eliminates the artifacts in the contemporary monitor. Also, as can be seen, the true patient results are quite stable and the enhanced algorithm records a proper trend.

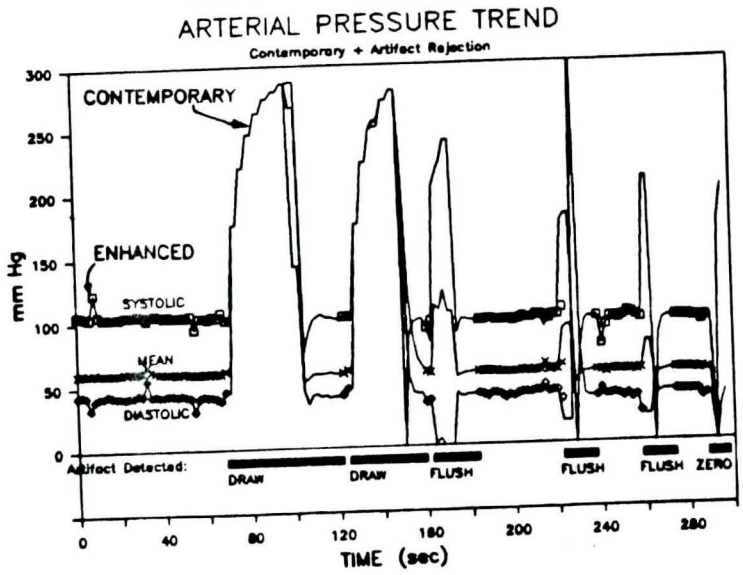

Fig. 7-8. Trend plot of data derived from a patient arterial pressure signal illustrating the consequences of blood drawing (DRAW), fast flushing (FLUSH), and zeroing the transducer (ZERO). The smooth "contemporary" curves are the data derived from the 2 second display updates of a Marquette 7000 series monitor. The discrete marks are the corresponding values obtained for the same patient waveform data with an enhanced artifact rejection algorithm. The bars below the plot show which type of artifact was detected and the time interval the artifact occurred. The sequence seen is DRAW, DRAW, FLUSH, FLUSH, then ZERO for a 300 second (5 minute interval) displayed. (Gardner RM, Monis SM, Oehler P: Monitoring direct blood pressure: algorithm enhancements. IEEE Comput Cardiol (1986 Conference). p. 607. 1987, with permission.)

Figure 7-9 shows a plot of systolic trend data for the same patient as in Figure 7-8 for the same time interval for the contemporary monitor and the enhanced algorithm. For the alarm limits set as shown, seven different alarms (six of them false) would have been activated during this 5 minute period. For the enhanced algorithm only one alarm was activated: at 240 seconds.

Clearly the enhanced algorithm produced dramatic improvements in the bedside monitor's ability to evaluate clinical data. From these experiments it can be concluded that:

1. Present monitoring systems allow far too much artifactual data to reach the monitors' display, trend buffer, and alarm logic.

2. The enhanced artifact rejection algorithm eliminates most of the false alarms caused by zeroing, flushing, and blood drawing.

3. The trend displays of the new algorithm are more representative of actual patient conditions.

4. Data sent from the bedside monitor to the computerized patient data management system are more valid and thus patient data management computer systems can be programmed to acquire patient data automatically.

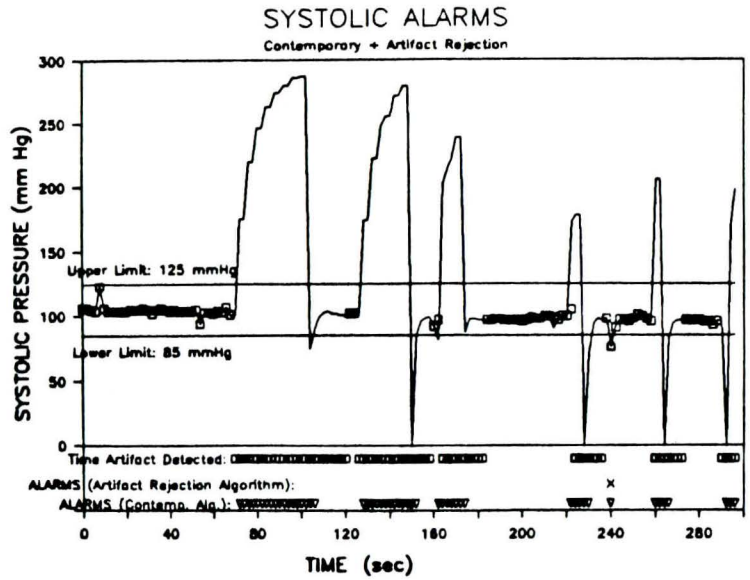

Fig. 7-9. Only the systolic pressure information from Figure 7-7. Superimposed are the upper (125 mmHg) and lower (85 mmHg) alarm limits for systolic pressure. On the bottom part of the figure are indicated the time intervals when artifacts were detected. The next line identified by ALARMS (artifact rejection algorithm) shows the alarms identified by the enhanced artifact rejection algorithm. Note there is only one "low" alarm at 240 seconds. The bottom line shows the alarms that would have been generated by the contemporary pressure monitor. (Gardner RM, Monis SM, Oehler P: Monitoring direct blood pressure: algorithm enhancements. IEEE Comput Cardiol (1986 Conference). p. 607. 1987 with permission.)

CONCLUSION

Clinical hemodynamic monitoring is now only about 25 years old. From a simple beginning 25 years ago there have been dramatic changes. The instrumentation and ability to evaluate the critically ill patient have been developed to a highly sophisticated level. Much has been learned about pressure measurements and how to acquire data with minimal errors. However, the clinical user should always be vigilant about the data derived from bedside monitors. Only after careful validation of the performance of these monitors and assessment of their limitations should the results, which they so effortlessly generate, be used for making clinical decisions. Methods that will aid in providing accurate data have been presented and, if carefully followed, should provide for better patient management.

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